



Optical material researches for frontier optical ceramics and visible fiber laser technologies

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Abstract: We have successfully developed a new technology of visible fiber laser, Pr-doped waterproof fluoro-aluminate glass fiber (Pr:WPFGF) laser. The significant achievements are as follows; 1) greater than 1-W and multi-color visible fiber laser oscillations, 2) visible laser pulse generation in a Pr-doped waterproof fluoride glass fiber using a graphene thin film as a saturable absorber, 3) demonstration of a novel design of a simple and compact tunable visible fiber laser, and 4) for more high power operation, fabrication of a Pr-doped double-clad structured waterproof fluoride glass fiber with a single-mode beam. These results are very useful for scientific and industrial applications.

Introduction: Recently, many research groups are studying visible lasers because the light sources are widely applicable for medicine, biology, metrology, optical storage, and display technology. Gas lasers and dye lasers have often been used in such scientific research, however, due to the delicate operation and the progress in nonlinear crystals, second harmonic generation (SHG) or optical parametric oscillator (OPO) techniques are now the mainstream in visible lasers development.

The primary visible laser oscillation is still fascinating. Ruby laser is the first laser, of course, also the first visible solid-state laser, but the other primary visible solid-state lasers have not been very successful because of the lack of good excitation sources. On the other hand, visible semiconductor lasers are well-developed for use in projector devices, and the power of a GaN laser diode (LD) is increasing more and more, and greater than 1-W blue (445 nm) and green (525 nm) LD packages are now produced by Nichia Corporation. These semiconductor lasers are very useful for excitation sources.

The trivalent rare earth ions, especially Pr^{3+} and Dy^{3+} , are very attractive for visible solid-state lasers because these generate several transitions in the red, orange, yellow, green, and blue spectral regions. Recently, many research groups have been studying visible lasers made from fluoride crystals or glasses with Pr^{3+} and Dy^{3+} ions ¹⁻⁸⁾ because the fluoride materials show lower phonon energy than the oxide ones; therefore, the luminescent intensity is higher without multiphonon relaxation. In the latest work, 2.9-W of red laser power was demonstrated in Pr:YLF excited by 2ω -OPS laser ⁸⁾.

In these background, we studied and developed the following technologies.

1. High power, over 1-W, Pr:WPFGF laser

In the present solid-state laser, fiber shape is commonly used, for example, Er- or Yb-doped fiber lasers, due to the excellent excitation efficiency, good output beam pattern, and alignment free design. Thus, fiber lasers have become more popular and more powerful. Based on these fiber shape advantages, several researchers have gotten into developing rare earth-doped fluoride fiber lasers. Smart et al. demonstrated a visible fiber laser with a ZBLAN glass excited by an Ar ion laser at 476.5 nm ¹⁾. A tunable fiber laser was also demonstrated in Pr:ZBLAN fiber excited by GaN-LD ²⁾. But ZBLAN glass fibers have poor chemical durability, especially that they are soluble in water. Thus a waterproof fluoride

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glass fiber is keen to be developed. For this purpose, we have successfully drawn rare earth-doped waterproof fluoro-aluminate glass fibers (RE:WPFGF) with low loss (0.1~0.3 dB/m) and demonstrated over 1-W multi-color laser oscillation in Pr:WPFGF excited by GaN-LDs.

2. Visible laser pulse generation in a Pr-doped waterproof fluoride glass fiber using a graphene thin film as a saturable absorber

Visible pulse generation, especially in a primary visible solid-state laser, is a very attractive research object. J. M. Sutherland et al. demonstrated 400-fs pulse laser in Pr:YLF using the Kerr-Lens mode-locking technique ⁹⁾. Several kinds of saturable absorbers (SA) have been developed so far, including SESAM ¹⁰⁾ and carbon nano-tube ¹¹⁾, which are often used in infrared mode-locked pulse lasers. The switching speed of a graphene SA was measured to be in the femtosecond range ¹²⁾. Since graphene makes a unique zero-gap linear band structure called Dirac cones, the absorbance is independent on the wavelength ¹¹⁾, and therefore, graphene has the possibility to work as an effective SA in the visible region. However, this kind of visible pulse laser with graphene SA has not been reported yet. We successfully demonstrated orange short pulse generation in Pr:WPFGF using a graphene thin film as a SA. The shortest pulse duration of 9.7 ns was observed in orange color. This result shows that a graphene thin film is an effective material as a SA switching device for visible pulse lasers.

3. Demonstration of a novel design of a simple and compact tunable visible fiber laser

Interaction between light and material is closely related to light wavelength; therefore, tunable lasers are widely used in many applications, for example, medicine, biology, and optical measurement systems. Generally, lasers emit at a single frequency; however, a laser medium with a broad emission spectrum, such as a laser dye or luminescent glass, can produce a tunable laser combined with a spectroscopic system, such as a grating or prism. In the following section, we propose and demonstrate a very simple way to achieve a tunable laser skillfully using the chromatic aberration of a lens relay and a slit-like effect of the optical fiber core.

4. Pr-doped double-clad structured waterproof fluoride glass fiber with single-mode beam

If we want more powerful visible fiber lasers, the increment of excitation power is an important factor. The most favorable excitation source for a solid-state laser is a laser diode because it directly changes electrical power to optical power with high efficiency. However, to increase the power of LDs, we have to provide sufficient beam quality for enlarging the emitter size of LDs. The most effective solution for using high-power LDs efficiently is to adopt a double-clad (DC) structure of the fiber cross-section. The DC structured fiber has an inner-clad surrounding a core that propagates a laser light. The inner-clad surrounded by an outer-clad is designed to accept the LD excitation source with low beam quality, and the excitation beam is effectively absorbed by core material through the inner-clad. The DC structured fiber is an effective way to maintain the beam quality of the fiber laser and to use the low beam quality excitation source. Now, many types of DC fiber cross-sections have been presented, such as D-shape and flower shape, and the DC structured fiber has become the standard of the fiber cross-section for high-power fiber lasers. Therefore, it is important not only to make progress on GaN-LD power but also to develop a DC structured fiber in visible fiber laser material in order to get higher visible fiber laser power. So we report that a Pr-doped double-clad structured waterproof fluoride glass fiber (Pr:DC-WPFGF) was successfully drawn, and the laser oscillation was demonstrated. The Pr:DC-WPFGF was designed to be a single-mode fiber and the beam-quality factor, M^2 , was measured and evaluated to be 1.0.

Experiment: Waterproof fluoride glasses in an AlF_3 system have been proposed by Iqbal et al. ¹³⁾ and Kanamori et al. ¹⁴⁾ An AlF_3 system fluoride glass is 500 times as water-resistant as ZBLAN glass ¹³⁾. Though many research groups have undertaken to draw an optical fiber from waterproof glass compositions (AlF_3 system), it has proven difficult to draw an optical fiber at low loss ¹⁴⁾. Finally, our group has successfully drawn the optical gain medium fibers with the properties of waterproof, low loss, and high concentration of rare earth ions.

1. High power, over 1-W, Pr:WPFGF laser

To get a more powerful laser that exceeds 1-W, firstly, the power of two GaN-LDs was combined by polarization beam splitter (PBS). Next, as a pulse operation mode was tested

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for increasing the output peak power, two GaN-LDs of 1.6-W rating were operated to provide the maximum peak power of 2.4 W at 5 Hz with 50% duty (100-ms on/off). We call this operation mode “overdrive pulse mode.” All the Pr:WPFGFs with 3000 ppm of Pr concentration were used as laser media. The Pr:WPFGF was fastened in a zirconia ferrule. The fiber core diameters, fiber lengths and reflectivity of output mirrors are listed in Table 1 (in Results and Discussion section). The pump source was a GaN-LD (NICHIA Corporation: NDB7875, 1.6-W) at 442 nm which is corresponding to the absorption peak of the Pr:WPFGF. The experimental setup of the Pr:WPFGF laser oscillation is illustrated in Fig.1.

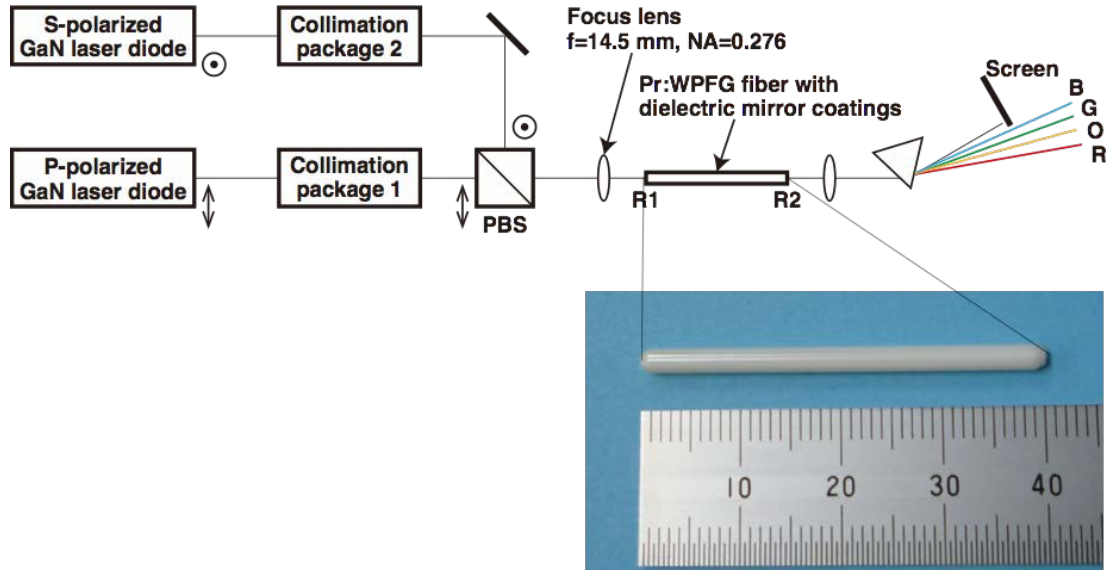


Fig.1 The setup of Pr:WPFGF laser excited by two-polarization-combined GaN-LDs

2. Visible laser pulse generation in a Pr-doped waterproof fluoride glass fiber using a graphene thin film as a saturable absorber

The experimental setup for the visible pulse laser oscillator and a photograph of the transcribed graphene thin film on a dielectric cavity output mirror are shown in Fig. 2. A commercially available single layer graphene on copper foil (Graphene Laboratory Inc.) was used in this experiment. In order to remove the film from the copper foil, the single layer graphene on copper foil was dipped in a 5% iron (III) nitrate water solution, and then the detached graphene was transcribed on a dielectric cavity output mirror (Fig. 2).

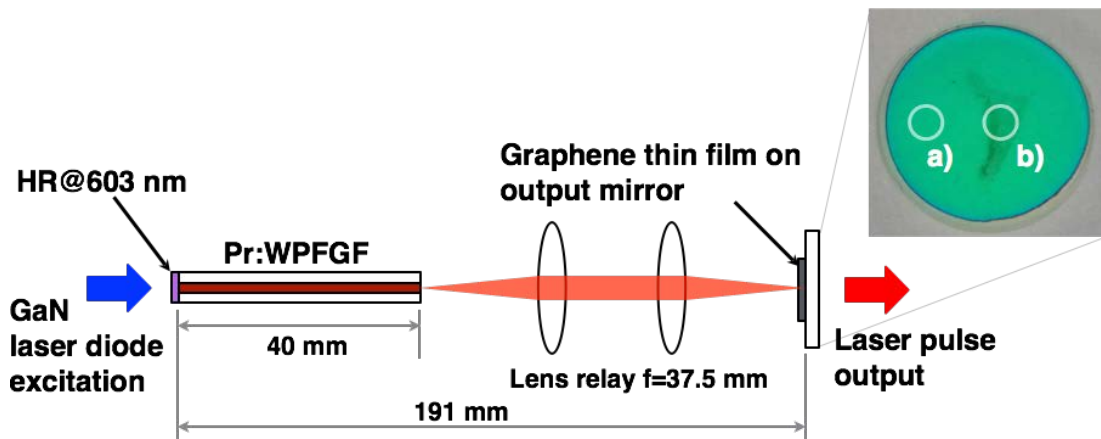


Fig. 2 Experimental setup for Pr:WPFGF visible pulse laser oscillator and a photograph of transcribed graphene thin film on a dielectric cavity output mirror. a) Focus spot for CW laser operation and b) Focus spot for pulse laser operation.

Next, we tested the CW laser operation at 603 nm with the experimental setup. A Pr:WPFGF was fixed in a zirconia ferrule. The Pr concentration of the fiber core was 3,000 ppm. The fiber's core diameter was 8 μ m and 40 mm long. Its numerical aperture was calculated to be 0.234 at 603 nm. Since its V-number was calculated to be 9.53 ($6.2(n/2)$) at 603 nm, the fiber was multimode. A GaN-LD (NICHIA Corp.: NDB7875, 1.6-W) was used as an excitation source, and the wavelength was 442 nm, which corresponds to the absorption

peak of the Pr:WPFGF. The excitation surface of the Pr:WPFGF in the zirconia ferrule has a high reflection dielectric multilayered coating ($R=99.9\% @ 603\text{nm}$), and the other end surface was non-coated; 3.5% loss through the non-coated surface was estimated. The fiber's output beam was focused on the graphene transcribed mirror (Edmund Optics; #64603, $R=99.1\% @ 603\text{ nm}$) by an aspheric lens relay (Edmund Optics; #49104, $f=37.5\text{ mm}$). The cavity length and the single pass optical distance were 191 and 216 mm, respectively. The laser pulses were measured on a Si-photo diode detector (Si-PD; Thorlabs, DET210). The spectrum of the CW laser oscillation was measured by a fiber optic spectrometer (Ocean Optics; HR2000).

3. Demonstration of a novel design of a simple and compact tunable visible fiber laser

A tunable laser is a light source that has coherence and wavelength selectivity. There have been many types of tunable lasers. Considering general tunable laser configuration, for example, Liu & Littman's¹⁵⁾ tunable laser, we find three essential elements:

- 1) Laser (gain) medium with broad emission spectrum;
- 2) Spatially dispersive optics for broad emission material, such as a grating or prism;
- 3) Selection mechanism of dispersed light source, such as a slit or mirror with an angle adjuster for a selected wavelength of the light direction.

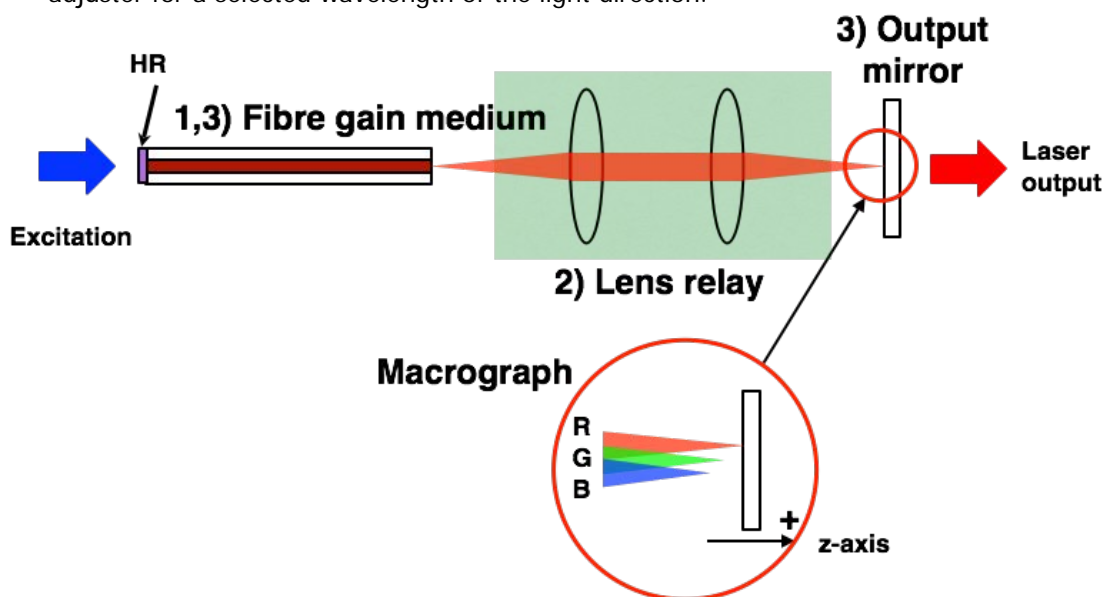


Fig. 3 Configuration of the presented simple and compact tunable laser. 1)-3) represent and explain the three elements in the text.

Of these elements, 2) and 3) are the bottleneck for a compact and simple tunable laser system because the usual dispersive optics require a widespread space. The configuration of our proposed tunable laser is shown in Fig.3. This configuration also contains the three following tunable laser elements:

- 1) Laser medium: a rare-earth doped active optical glass fiber;
- 2) Dispersive optics: lens relay for spatial dispersion of the light source; and
- 3) Selection mechanism: a slit-like effect of the optical fiber core and the output mirror that moves in z-axis (laser output direction) for image relay.

Glass material provides a local field of rare-earth elements in its inhomogeneous broadening of the energy bands in the elements, and therefore, a rare-earth doped glass fiber can function as a broad luminescent material. The luminescent spectrum of Pr:WPFG is illustrated in Fig.4. As shown in Fig.4, we can apply Pr:WPFG as a broad luminescent material for an optical fiber core. Next, the usual transparent optics naturally have chromatic aberration; thus, the lens relay can operate as dispersive optics to control the focus length of the cavity. Finally, as the focusing distance changes with wavelength due to the chromatic aberration, by putting the output mirror at the image relay point of the optical fiber core surface for each color, we can select the wavelength with the moving output mirror in the z-axis because the fiber core operates like a slit.

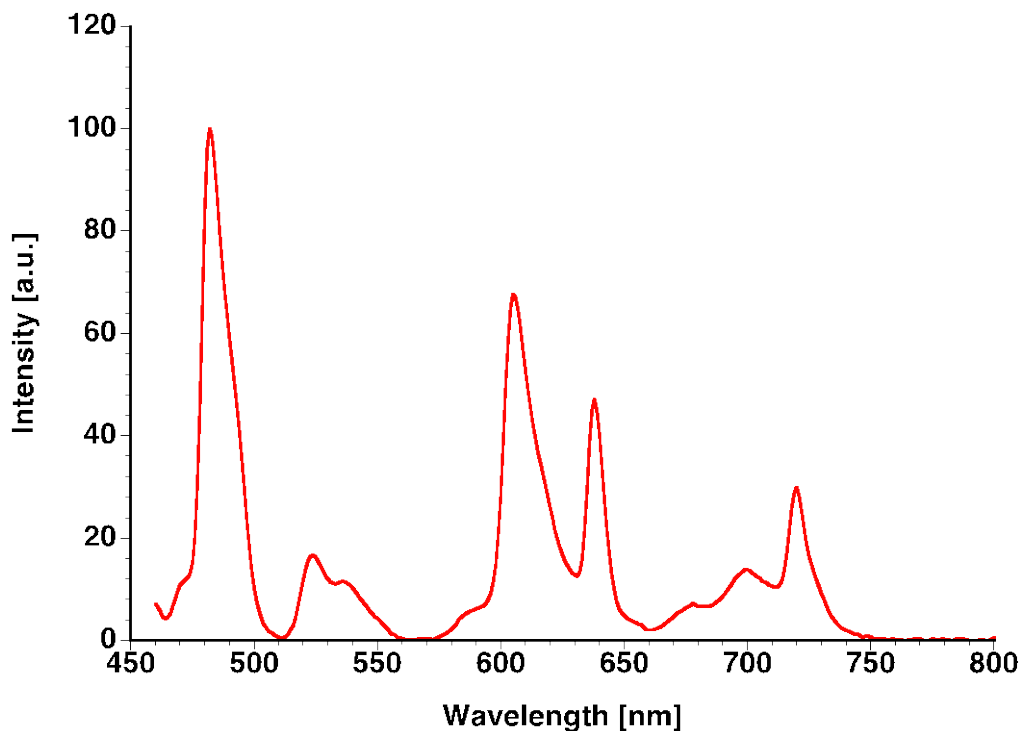


Fig. 4 *Luminescent spectrum of Pr:WPFG.*

We tested the tunable laser's operation in an experimental setup as shown in Fig.3. A Pr:WPFG fiber fixed in a zirconia ferrule was used as a broadband gain fiber. The Pr concentration of the fiber core was 3,000 ppm. The fiber's core diameter and length were 8 μm and 40 mm, respectively. Its numerical aperture was calculated to be 0.233 to 0.234 between 600 and 630 nm.

A GaN-LD (gallium nitride-laser diode) (NICHIA Corp.: NDB7875, 1.6 W) was used as an excitation source and the emission wavelength was 442 nm, which corresponds to the absorption peak of the Pr:WPFG fiber. The excitation surface of the Pr:WPFG fiber in the zirconia ferrule had a high reflection dielectric multilayered coating ($R = 99.9\%$, 600-660 nm). The other end surface was non-coated and we estimated a 3.5% loss through the non-coated surface. The fiber output beam was focused on the mirror (Edmund Optics; #47289) with an aspheric lens relay (Edmund Optics; #49104, $f = 37.5$ mm). The cavity length was 191 mm and the cavity output mirror position of the z-axis was adjusted using a stage micrometer. The spectrum of the CW laser oscillation was measured by a fiber optic spectrometer (Ocean Optics; HR2000).

4. Pr-doped double-clad structured waterproof fluoride glass fiber with single-mode beam

We tested a CW red laser oscillation with the experimental setup illustrated in Fig. 5. A Pr:DC-WPFGF was prepared for this experiment. The fiber's core diameter was 5.2 μm , the inner-clad diameter was 14 μm and the outer-clad diameter was 270 μm . The numerical apertures (NA) of the core and the inner-clad were 0.08 and 0.29, respectively. Since its V-number is calculated to be 2.045 (< 2.405) at 639 nm, the fiber is expected to be a single-mode fiber. The Pr concentration of the fiber core was 3,000 ppm. The fiber length was 100.4 mm. Both fiber end surfaces of the Pr:DC-WPFGF have dielectric multilayered coatings. The excitation surface has a high reflection mirror ($R=99.5\% @ 639$ nm, $27.3\% @ 600$ nm, $4.6\% @ 442$ nm ($T=95.4\%$)), and the other end surface has a partial reflection mirror ($R=61.7\% @ 639$ nm, $2.5\% @ 600$ nm, $73.7\% @ 442$ nm ($T=26.3\%$)). A GaN-LD (NDB7875E, 1.6-W; NICHIA Corp.) was used as an excitation source, and the wavelength was 442 nm, which corresponds to the absorption peak of the Pr:DC-WPFGF¹⁶⁾. The collimation package includes a collimation lens ($f=8.0$ mm, $NA=0.5$) and an anamorphic prism pair with a magnification of 4. The slow axis of GaN-LD was set to the magnifying axis in the anamorphic prism pair. The shaped LD beam was focused onto the Pr:DC-WPFGF excitation fiber end surface by a focusing lens with a focal length of 14.5 mm and an NA of 0.28 (GLC-14.5-8.0-405; CVI). The input-output characteristics of CW red laser power were measured by an optical power meter (OPHIR; model 3A) with route a) in Fig. 5. The spectrum of the CW red laser oscillation was measured by a fiber optic spectrometer (Ocean Optics; HR2000).

The beam-quality factor of the CW red laser was measured by route b) in Fig. 5. A collimation lens ($f=11.0$ mm, $NA=0.26$; A220TM-A, THORLABS) and a focus lens ($f=30.0$

mm, NA=0.42; #47-633, Edmund Optics) were used. The beam spot size dependence on the z-axis, which is defined as the laser propagation direction, was measured by a micro-beam profiler (MBP-100-USB; Newport).

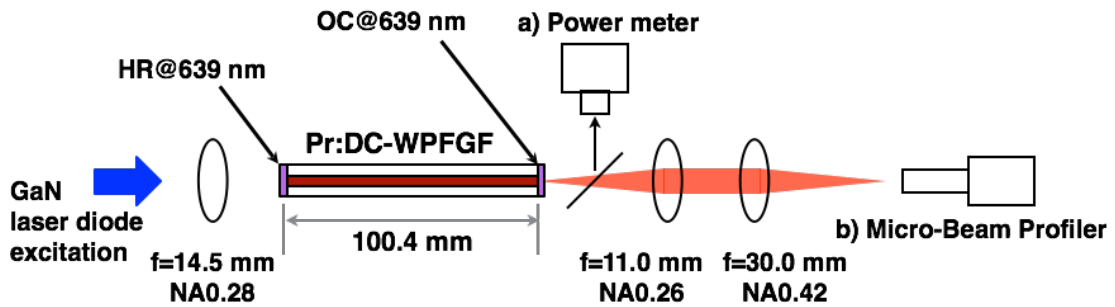


Fig. 5 Experimental setup for visible fiber laser oscillator in Pr:DC-WPFGF. a) Measurement for input-output characteristics on CW red laser oscillation, and route b) Measurement for beam-quality factor.

Results and Discussion: The four significant experimental research advances are explained as follows.

1. High power, greater than 1-W, Pr:WPFGF laser

The results are shown in Fig. 6. Greater than 1-W laser oscillations were demonstrated in cyan, green and red colors. The visible laser performances with fiber and mirror conditions are also summarized in Table 1. Orange laser was also demonstrated at 0.52W because of existence of self-absorption band ($^3H_4 \rightarrow ^1D_2$). Historical study of Pr-doped primary red laser development is shown in Fig. 7. Our result of 1.8 W high-power red fiber is still the world record in primary red fiber lasers.

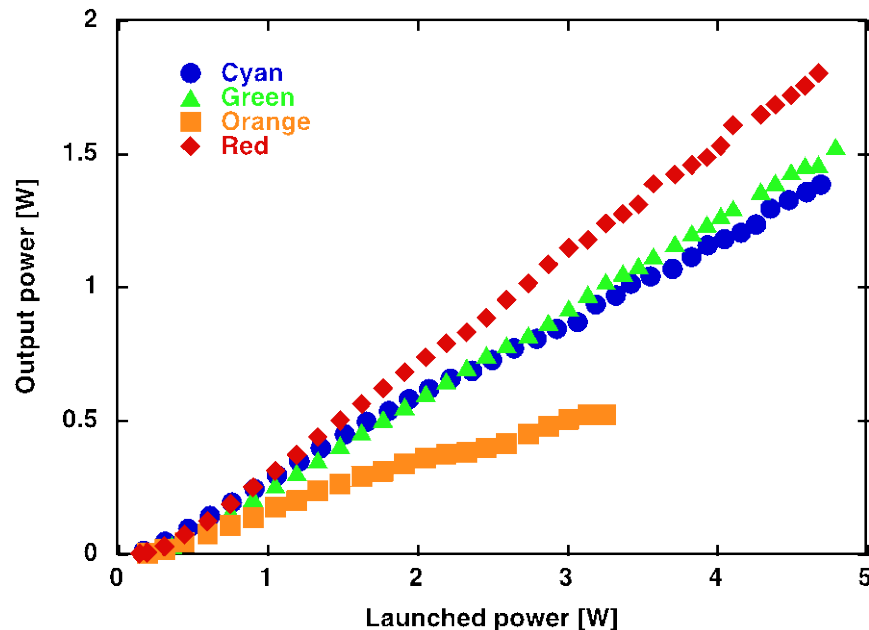


Fig. 6 Visible Pr:WPFGF laser characteristics. Launched power includes coupling and absorption losses.

Table 1 Summary of visible laser performances with fiber and mirror conditions.

	Cyan	Green	Orange	Red
Oscillation wavelength [nm]	493.6	522.2	605.6	638.6
Maximum power [W]	1.38	1.53	0.52	1.80
Slope efficiency [%]	30.0	33.8	20.0	41.7
Maximum Conversion efficiency [%]	29.7	31.8	17.7	38.4
Threshold power [mW]	97	281	221	282
Core diameter [μ m]	11	11	15	14
Fiber length [mm]	40	40	40	60
Reflectivity of output mirror [%]	94.1	94.9	91.1	60

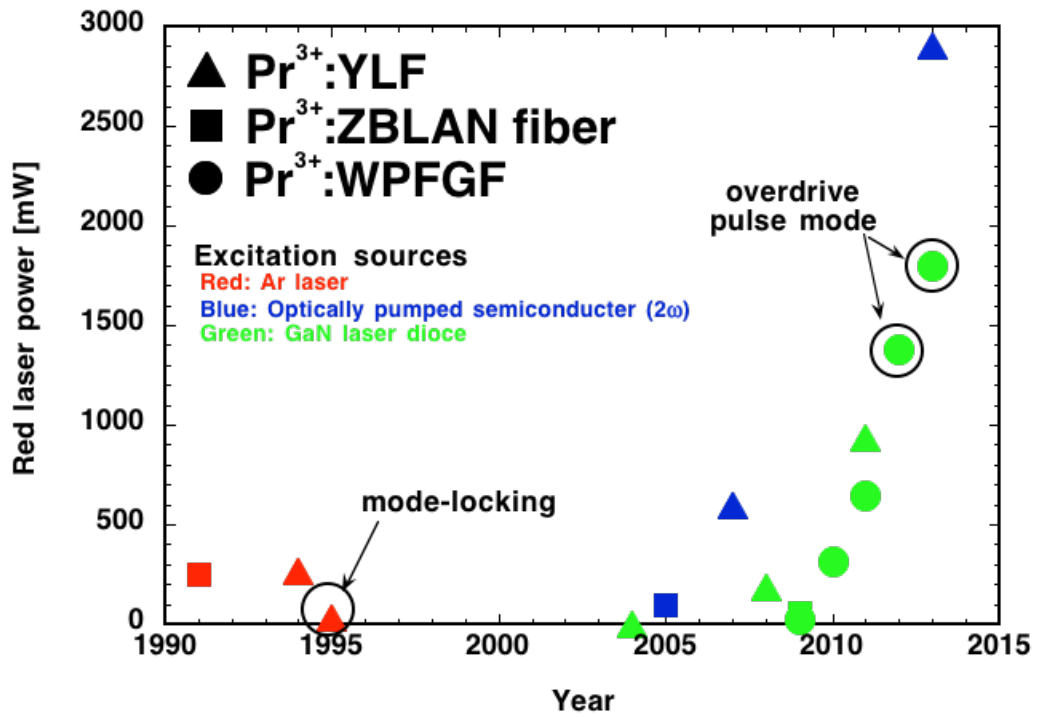


Fig. 7 Historical study of Pr-doped primary red laser development. Green circles are our results.

2. Visible laser pulse generation in a Pr-doped waterproof fluoride glass fiber using a graphene thin film as a saturable absorber

The input-output characteristics of the CW operation are shown in Fig. 8. As shown in Fig. 2, the graphene transcribed mirror had parts with and without graphene thin film. When we demonstrated the CW laser oscillation, we used the mirror part without graphene thin film (Fig. 2, part a)). In this case, we did not observe any pulse generation. When the launched power was 522 mW at the maximum, the observed output power was 1.0 mW. The peak oscillation wavelengths were 603 nm.

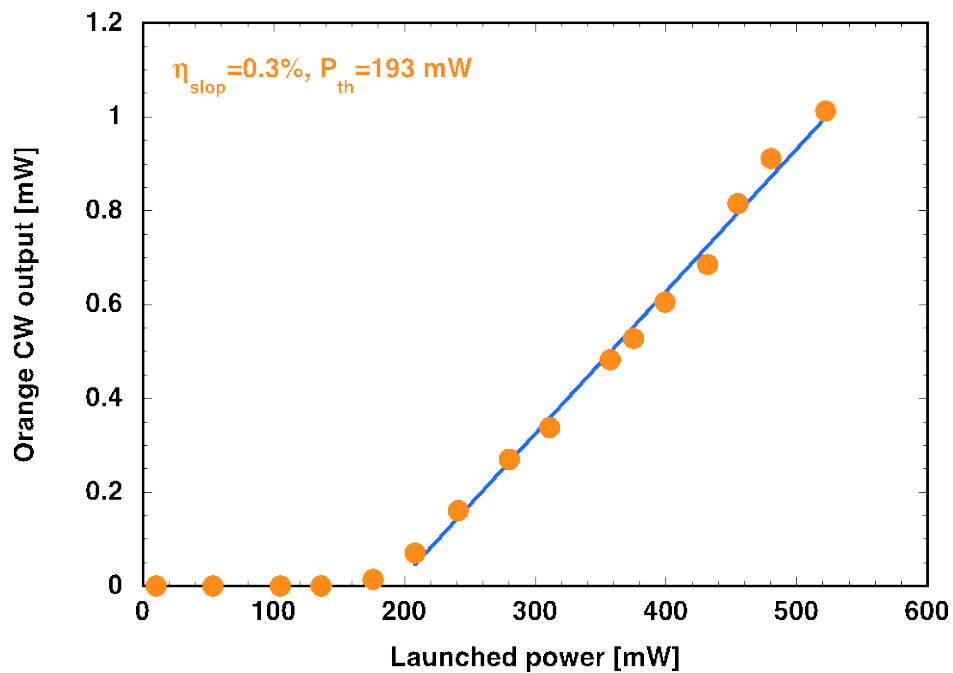


Fig. 8 Orange CW input-output characteristics

Next, we tested the pulse laser generation. When we demonstrated it, we used the mirror part with graphene thin film (Fig. 2, part b)). As the graphene SA properties were not uniform in the graphene thin film area, we searched for suitable points of the transcribed graphene thin film on the cavity output mirror by moving the mirror in the x-y plane (z-axis

means the direction of the light propagation). Finally, we observed two modes of laser oscillation pulses (Figs. 9a and b).

One operation mode was the continuous pulse generation shown in Fig. 9a. The pulse repetition period was $2.61\ \mu\text{s}$, and the pulse duration's FWHM was $0.47\ \mu\text{s}$ (Fig. 9a). In this experiment, since the SA properties of the transcribed graphene were not uniform in the film area on the mirror (as explained above), the pulse repetition periods and the pulse durations were slightly different from all the places, and the possibility of the existence of two or more pulse repetition periods was also shown in another place observation. Therefore, in this report, we illustrated a typical continuous pulse, as shown in Fig. 9a.

The second pulse operation is a suddenly generated giant pulse with a moving x-y plane of graphene thin film on the mirror. This is a single pulse (Fig. 9b). In this measurement, there was an additional OD2 filter (1% transmittance) in front of the Si-PD detector compared to the experimental setup of the continuous pulse generation, and the pulse peak intensity was ten times larger than the continuous pulse peak without an OD2 filter. Therefore, we estimated that the giant pulse is three orders of magnitude larger than the continuous pulse peak. The pulse duration of the giant single pulse was measured to be $9.7\ \text{ns}$ at $522\ \text{mW}$ blue LD excitation, and the duration was much less than the continuous one.

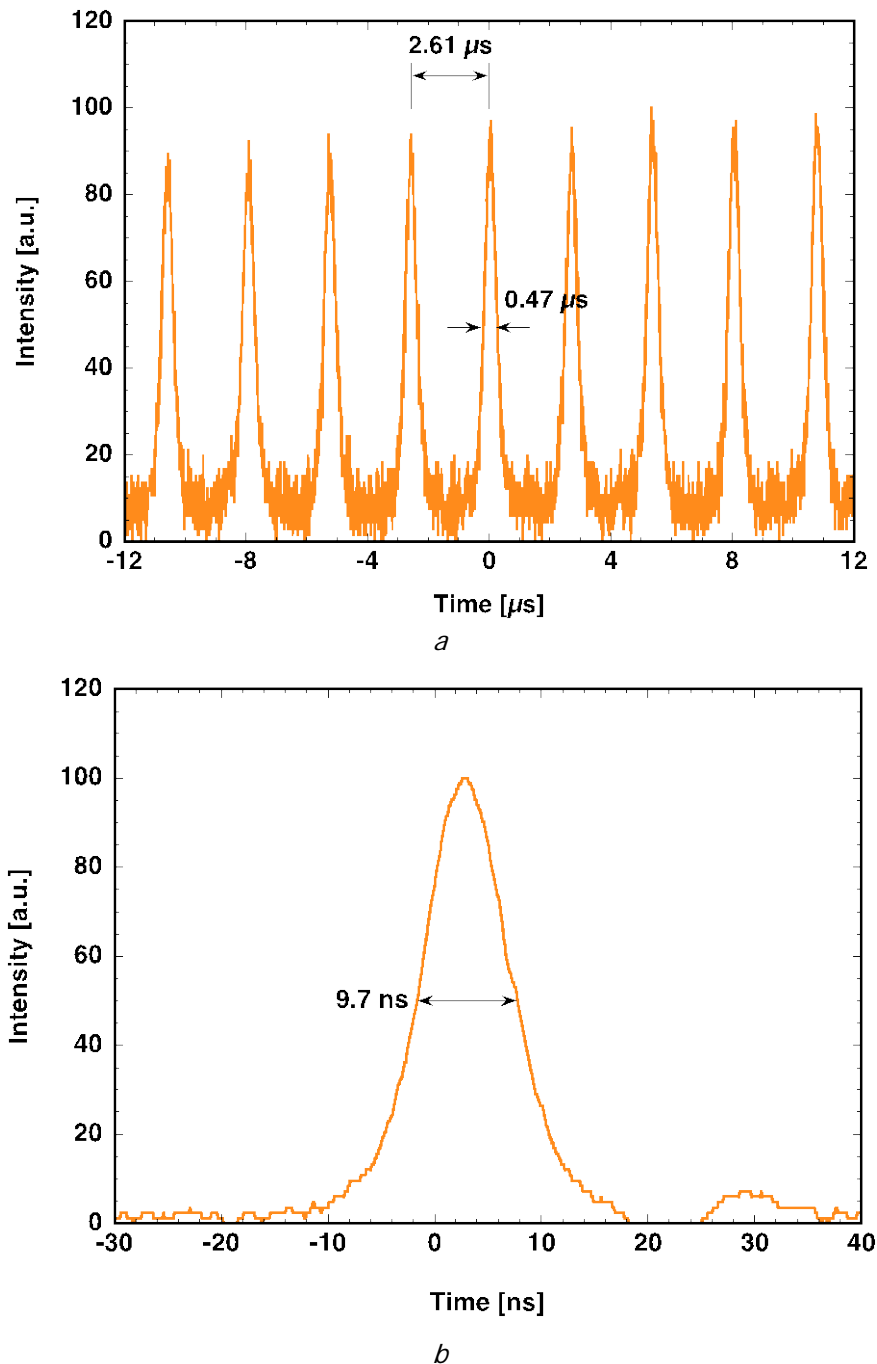


Fig. 9 Pulse laser generation in Pr:WPFGF.

a Continuous pulse generation mode

b Single giant pulse generation mode

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These two pulse generation mechanisms are obviously different. The former corresponds to the switching process of a few percent of breaching of the graphene thin film. The accumulated energy in the oscillation cavity by CW excitation is expressed by the convolution of the CW excitation power with radiative decay:

$$E_{cavity}(t) \propto (1 - e^{-t/\tau_f}). \quad (1)$$

Here we estimate the rate of the pulse output energy to the maximum energy confined in the cavity using 51.3 μs of the Pr:WPFG lifetime¹⁷⁾. Since the cavity with graphene switched and released the stored energy pulses every 2.61 μs , the pulse energy's maximum rate is calculated to be less than 5.0% of the maximum cavity energy. Since the repetition period of the 2.61 μs is much longer than the round trip time of the cavity (1.44 ns), the pulse was generated by a cavity dumping process.

On the other hand, the latter mechanism may correspond to the switching of the nearly full breaching of the graphene thin film. Wagner et al. reported that the pulse duration becomes shorter as the rate of the initial state population inversion density to the threshold state one increases¹⁸⁾. Thus, the following three situations are considered: 1) the case that the initial population inversion state of the giant single pulse in our experiment is larger than the continuous pulse, or 2) the case that the threshold state population inversion density of the giant single pulse is smaller than that of continuous pulse, or 3) the mixed situation of the both above cases. The importance of understanding this phenomenon is also supported by the fact that the giant pulse peak intensity is three orders of magnitude larger than the continuous pulse peak intensity. If we can control the switching process with graphene thin film, such understanding may give variety of pulse generations.

Fluoride glass materials show about 10-20 nm of spectral bandwidth¹⁷⁾, and the bandwidth is wide enough for generating ultra-short pulse lasers. According to previous research¹²⁾, the switching speed of the graphene that reaches femtoseconds and this broadband spectrum property of fluoride glass materials help us to demonstrate a primary visible ultra-short pulse laser with a mode-locking technique by a graphene SA.

3. Demonstration of a novel design of a simple and compact tunable fiber laser

Figure 10 shows the experimental results of the tunable properties. The wavelength lengthens as the cavity length increases. Only 130 μm of z-axis moving distance was required to obtain about 20 nm of tunability.

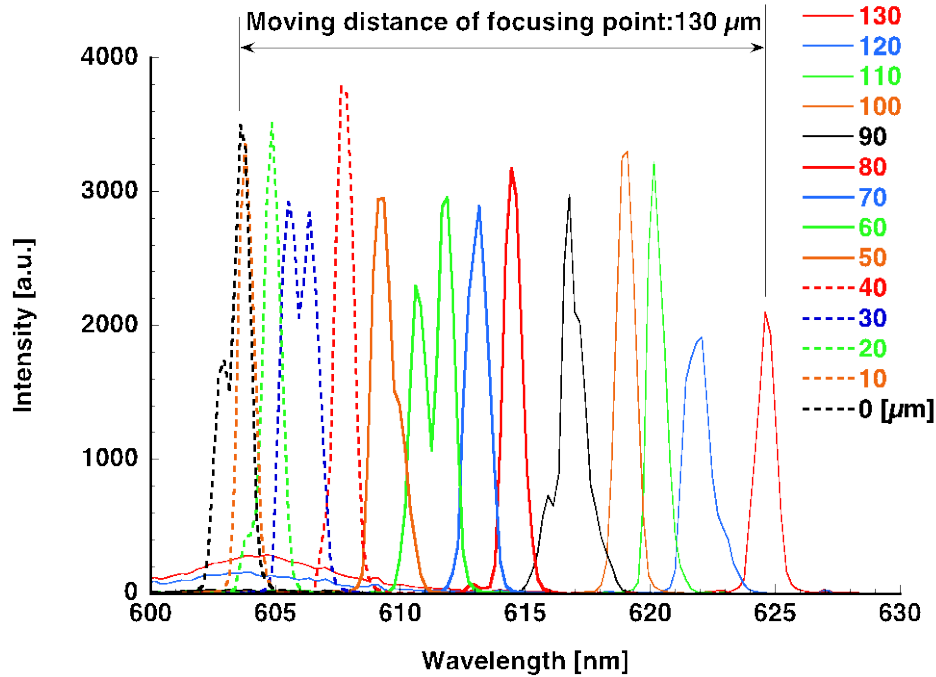


Fig.10 Experimental result of the presented simple and compact tunable laser.

By applying the chromatic aberration of the lens relay to dispersive optics, we created a simple and compact tunable laser. The z-axis moving distance to obtain 20 nm of tunability was only 130 μm . This 130 μm of moving distance is a very distinctive value because it is much smaller than that of tunable laser systems with gratings and is much larger than that

with an etalon in nm-order precision. Therefore, there is no need for a larger space or complicated and high precision devices.

This configuration, as shown in Fig.3, has other merits as well. First, if we put an appropriate saturable absorber on the output mirror, such as a graphene, carbon nanotube, or SESAM (semiconductor saturable absorber mirror), the laser can operate as a Q-switch¹⁹⁾ or mode-locked tunable fiber laser. Second, we only demonstrated this laser between orange and red, but this method can be easily used for any wavelength that has active fiber lasers, such as Pr (0.48, 0.52, 0.61, 0.64, 0.72 μm), Nd (1.06 μm), Yb (1.03 μm), Er (1.55 μm), and Tm (2.0 μm). Third, this method can also be applied to waveguide-type gain media, such as semiconductor waveguides.

4. Pr-doped double-clad structured waterproof fluoride glass fiber with single-mode beam

The input-output characteristics of the CW red laser oscillation are shown in Fig. 11. The maximum output power was measured to be 251.7 mW at 701.1-mW GaN-LD excitation. The slope efficiency and threshold power were calculated to be 43.4% and 120.6 mW, respectively. The absorbed excitation GaN-LD power in the Pr:DC-WPFGF was estimated to be 90% of launched GaN-LD power.

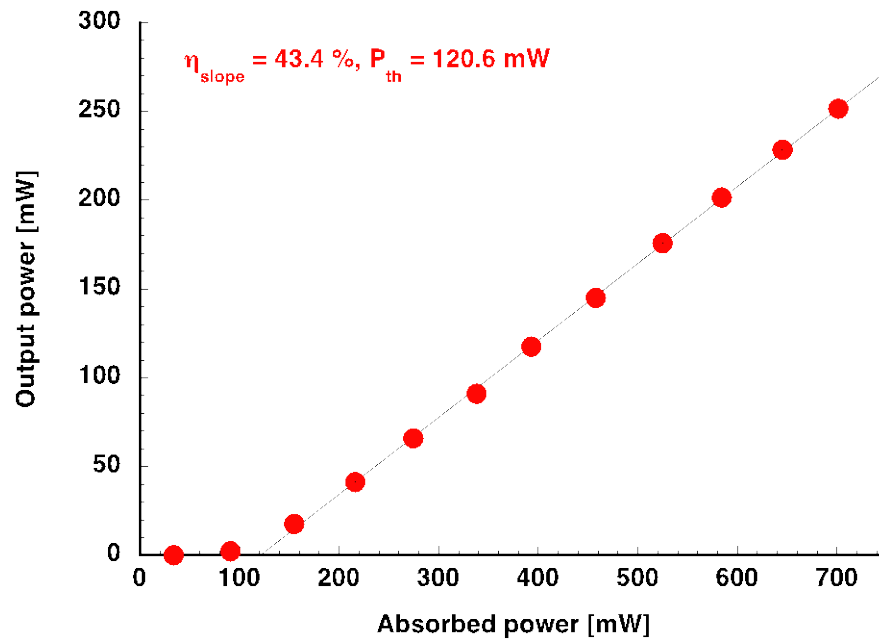


Fig. 11 Input-output characteristics of CW red laser oscillation.

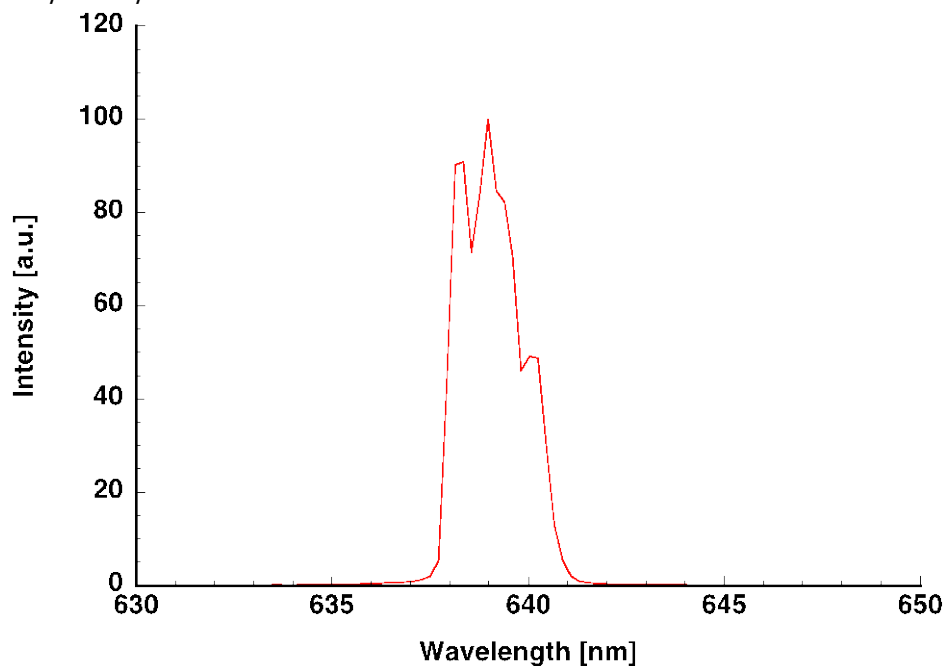


Fig. 12 Spectrum of CW red laser oscillation in Pr:DC-WPFGF.

The measured spectrum of CW red laser oscillation is illustrated in Fig. 12. The peak wavelength and spectral width of FWHM were measured as 639.0 nm and 2.3 nm. The beam spot size dependence on the z-axis of the Pr:DC-WPFGF laser is illustrated in Fig. 13. The beam-quality factors²⁰⁾ were evaluated in horizontal and vertical axes. The beam radius was described as Eq. (2).

$$W(z) = W_0 \left[1 + \left(\frac{z}{z_R} \right)^2 \right]^{1/2} \quad (2)$$

where $W(z)$ is beam radius at z , W_0 is beam waist radius, and z_R is Rayleigh range. Rayleigh range was expressed as the following equation.

$$z_R = \frac{\pi W_0^2}{M^2 \lambda} \quad (3)$$

where λ is wavelength, M^2 is beam-quality factor. The beam-quality factors in horizontal and vertical axes are evaluated to be $M^2_{\text{horizontal}} = 1.04$ and $M^2_{\text{vertical}} = 1.00$; therefore, it is considered that the output laser beam from Pr:DC-WPFGF is confirmed as a single-mode beam. The beam waist diameters and Rayleigh ranges in the horizontal and vertical axes in this setup are also calculated to be 20.6, 19.4 μm and 505, 463 μm , respectively. The beam pattern image at the beam waist point is also illustrated in Fig. 13.

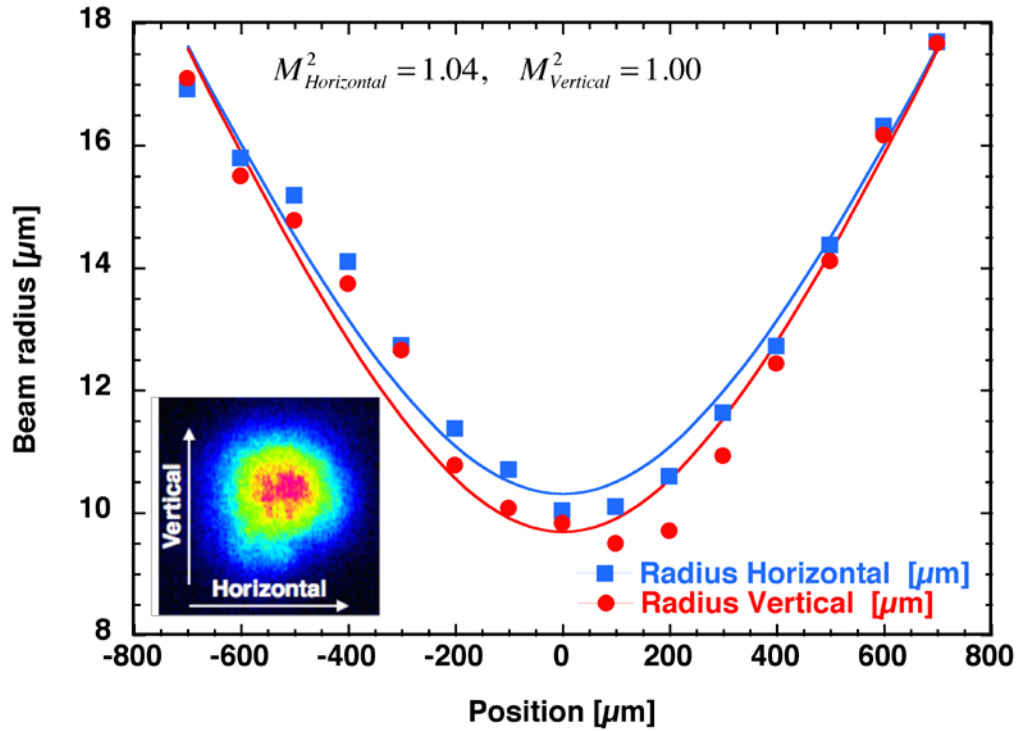


Fig. 13 Beam-quality factor measurement on Pr:DC-WPFGF laser.

Summary: In view of photon beam cost, GaN-LD power will probably be even more significant in the next decade. As research all over the world pursues higher power GaN-LDs, we will soon have multi-watt GaN-LDs with multi-emitter array structured bars, which will be stacked to make hundreds of W modules in the future, as in the development of infrared high-power semiconductor lasers. The power increment of GaN-LDs will usher in the same progress that proceeded in Nd:YAG, or Yb- and Er-doped fiber lasers in primary visible solid-state fiber lasers. Achieved and target items for visible solid-state laser development are shown in Fig. 14.

a) High-power visible CW laser: Greater than 1-W class of visible lasers excited by GaN-LDs was accomplished. Further research on higher power GaN-LDs, power combiners, and double-cladding fiber techniques for the visible region will produce a 10-W class or more powerful primary visible fiber lasers. Of course, these high-power visible lasers are very useful for industrial uses, including marking, cutting, welding, and paste-free soldering.

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b) *High-power tunable visible lasers and ultra-violet generation:* Since visible fiber laser power is increasing, we can easily imagine the appearance of high-power solid-state visible tunable fiber lasers, because wide range tunability was already demonstrated by a Pr:ZBLAN fiber laser²⁾ excited by GaN-LDs. Another fascinating possibility is a compact ultra-violet laser because visible lasers reach ultra-violet region by SHG. Some SHG trials for visible lasers have been reported, for example, an intra-cavity system with a Pr:YLF and a LBO crystal that generates 346 mW at 320 nm²¹⁾. Borate crystals, such as BBO, LBO, and CLBO, are mainly used for SHG crystals for generating visible light. The development of new crystals²²⁾ that work on this wavelength region and the QPM structure on BBO or quartz²³⁾ are strongly desired for the high beam quality of the ultra-violet region.

c) *Ultra-short visible fiber laser system:* Fluoride glass materials display broad fluorescence spectra. Based on this property, we made a visible ultra-short pulse laser with a mode-locking technique. Although a mode-locking pulse laser for a primary visible solid-state laser was already achieved using Pr:YLF⁹⁾, the wider fluorescence spectra derived from an inhomogeneous crystal field in glass host materials can produce a shorter pulse duration. To generate an ultra-short pulse, appropriate saturable absorbers are indispensable. There are many candidates for saturable absorbers, for example, laser dyes, semiconductor saturable absorber mirrors (SESAMs), carbon nano-tubes, and graphenes. As the research on saturable absorbers progresses in the visible region, a primary ultra-short visible fiber laser will be suitably designed, and research using such ultra-short visible fiber lasers will expand.

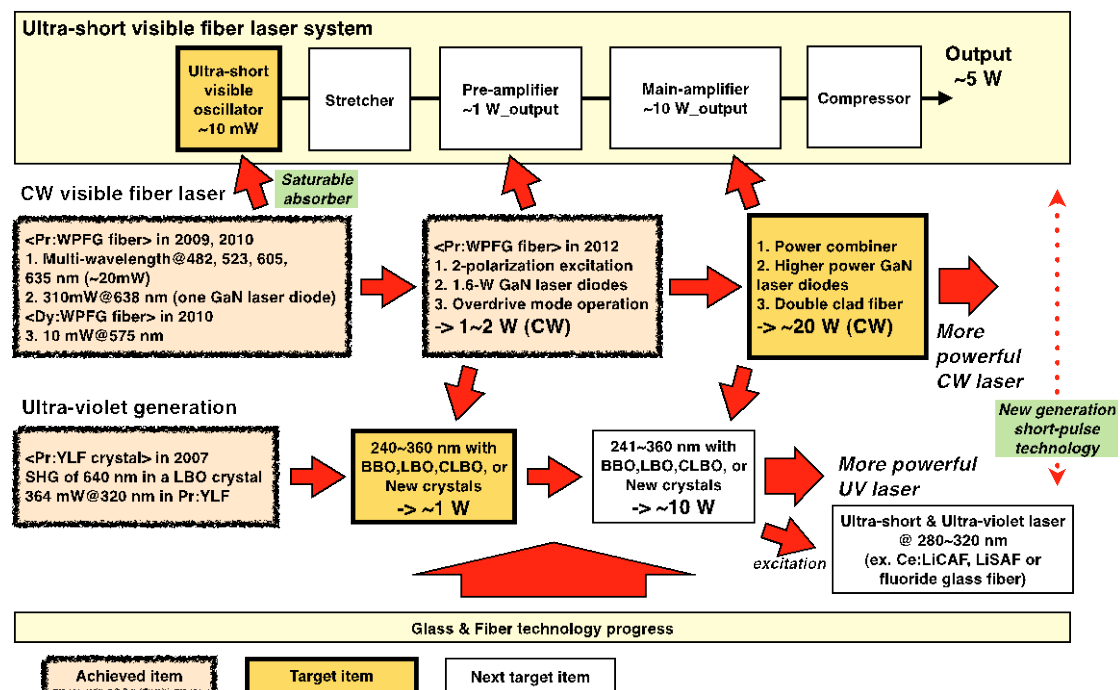


Fig.14 Achieved and target items for visible solid-state laser development.

References

- 1) R. G. Smart, J. N. Carter, A. C. Tropper, D. C. Hanna, S. T. Davey, S. F. Carter and D. Szebesta: Optics Communications **86** (1991) 333.
- 2) H. Okamoto, K. Kasuga, I. Hara and Y. Kubota: Optics Express **17** (2009) 20227.
- 3) Y. Fujimoto, O. Ishii and M. Yamazaki: Electronics Letters **45** (2009) 1301.
- 4) J. Nakanishi, T. Yamada, Y. Fujimoto, O. Ishii and M. Yamazaki: Electronics Letters **46** (2010) 1285.
- 5) J. Nakanishi, T. Yamada, Y. Fujimoto, O. Ishii and M. Yamazaki, Sub-watt output power at 638nm in wavelength by direct oscillation with Pr-doped waterproof fluoro-aluminate glass fiber laser, *2011 Conference on Lasers and Electro-Optics Europe and 12th European Quantum Electronics Conference (CLEO@/Europe - EQEC 2011)*, IEEE Conference Publications Operations, ICM - International Congress Centre, Munich, Germany (2011).
- 6) J. Nakanishi, Y. Horiuchi, T. Yamada, O. Ishii, M. Yamazaki, M. Yoshida and Y. Fujimoto: Optics Letters **36** (2011) 1836.
- 7) Y. Fujimoto, O. Ishii and M. Yamazaki: Electronics Letters **46** (2010) 586.
- 8) P. W. Metz, F. Moglia, F. Reichert, S. Müller, D. T. Marzahl, N. O. Hansen, C. Kränkel and G. Huber, Novel Rare Earth Solid State Lasers with Emission Wavelengths in the Visible Spectral Range, *CLEO@/Europe - IQEC 2013*, Optical Society of America, ICM - International Congress Centre, Munich, Germany (2013).
- 9) J. M. Sutherland, P. M. W. French, J. R. Taylor and B. H. T. Chai: Optics Letters **21** (1996) 797.
- 10) Y. C. Noh, Y. S. Lim, J. H. Lee and J. S. Chang: Electronics Letters **36** (2000) 1288.
- 11) S. Yamashita: Journal of Lightwave Technology **30** (2012) 427.
- 12) J. M. Dawlaty, S. Shivaraman, M. Chandrashekar, F. Rana and M. G. Spencer: Applied Physics Letters **92** (2008) 042116.
- 13) T. Iqbal, M. R. Shahriari, G. Merberg and G. H. Sigel: Journal of Materials Research **6** (1991) 401.

- 14) T. Kanamori, K. Oikawa, S. Shibata and T. Manabe: Japanese Journal of Applied Physics **20** (1981) L326.
- 15) K. Liu and M. G. Littman: Optics Letters **6** (1981) 117.
- 16) Y. Fujitomo, M. Murakami, J. Nakanishi, T. Yamada, O. Ishii and M. Yamazaki, Visible lasers in waterproof fluoro-aluminate glass fibers excited by GaN laser diodes, *Advanced Solid-State Lasers Congress*, Optical Society of America, Washington, DC, Marriott Paris Rive Gauche Hotel and Convention Center Paris, France (2013).
- 17) Y. Fujimoto, J. Nakanishi, T. Yamada, O. Ishii and M. Yamazaki: Progress in Quantum Electronics **37** (2013) 185.
- 18) W. G. Wagner and B. A. Lengyel: J Appl Phys **34** (1963) 2040.
- 19) Y. Fujimoto, T. Suzuki, R. A. M. Ochante, T. Hirayama, M. Murakami, H. Shiraga, M. Yoshida, O. Ishii and M. Yamazaki: Electronics Letters **50** (2014) 1470.
- 20) W. Koechner, Solid-State Laser Engineering, Springer, New York (2006).
- 21) A. Richter, E. Heumann, G. Huber, V. Ostroumov and W. Seelert: Optics Express **15** (2007) 5172.
- 22) E. G. Villora, K. Shimamura, K. Sumiya and H. Ishibashi: Optics Express **17** (2009) 12362.
- 23) S. Kurimura, M. Harada, K. Muramatsu, and M. Ueda, Quasi-phase-matched second-harmonic generation at vacuum ultraviolet 193 nm, *The Conference on Lasers and Electro-Optics (CLEO)/The International Quantum Electronics Conference (IQEC)*, Optical Society of America, Baltimore Convention Center, Baltimore, MD, USA (2011).

List of Publications and Significant Collaborations that resulted from your AOARD supported project: including other topic with our AOARD project:

a) papers published in peer-reviewed journals,

- 1) "Suppression of photo-darkening effect by Ca additive in Yb-doped silica glass fibre", S. Sugiyama, Y. Fujimoto, M. Murakami, H. Nakano, T. Sato, and H. Shiraga, Electron. Lett., **Vol. 49** (2013) pp.148-149.
- 2) "Visible fiber lasers excited by GaN laser diodes" (*Invited Review paper*), Yasushi Fujimoto, Jun Nakanishi, Tsuyoshi Yamada, Osamu Ishii, Masaaki Yamazaki, Progress in Quantum Electronics **37** (2013) pp.185-214.
- 3) "Short-length fiber laser oscillation in 4-mm Nd-doped silica fiber fabricated by zeolite method", Motoichiro Murakami, Yasushi Fujimoto, Shinji Motokoshi, Tatsuhiro Sato, Hiroyuki Shiraga, Optics Communications **328** (2014) pp.121-123.
- 4) "Generation of orange pulse laser in waterproof fluoride glass fiber with graphene thin film", Y. Fujimoto, T. Suzuki, R. A. M. Ochante, T. Hirayama, M. Murakami, H. Shiraga, M. Yoshida, O. Ishii, and M. Yamazaki, Electron. Lett., **Vol. 50** (2014) pp.1470-1472.
- 5) "Design of Simple and Compact Tunable Fibre Laser -(*Featured article*)", Y. Fujimoto, O. Ishii, and M. Yamazaki, Electron. Lett., **Vol. 51** (2015) pp.925-926.
- 6) "Development of low photo-darkening Yb-doped silica glass fiber by co-doping of group 2 element", Yuki Sakaguchi, Yasushi Fujimoto, Masaya Masuda, Noriaki Miyanaga, and Hitoshi Nakano, J. Non-Cryst. Solids, **440** (2016) pp.85-89.
- 7) "Single-mode visible laser oscillation in Pr-doped double-clad structured waterproof fluoro-aluminate glass fiber", S. Kajikawa, T. Terao, M. Yoshida, S. Motokoshi, O. Ishii, M. Yamazaki, Y. Fujimoto, Electron. Lett., **Vol. 52** (2016) pp.861-863.

b) papers published in peer-reviewed conference proceedings,

- 1) "Visible lasers in waterproof fluoro-aluminate glass fibers excited by GaN laser diodes", Y. Fujimoto, M. Murakami, J. Nakanishi, T. Yamada, O. Ishii and M. Yamazaki, 2013 Advanced Solid-State Lasers (ASSL), **AM2A.2**, 27 October - 01 November 2013, Paris Marriott Rive Gauche Hotel and Convention Center, Paris, France.
- 2) "Development on advanced functional optical materials and fibers - (*invited*)", Y. Fujimoto, The 2013 Asia Communications and Photonics Conference (ACP), **AW4C.4**, 12-15 November 2013, The Beijing Conference Center, China.
- 3) Development on advanced functional optical fibers and materials in ILE - (*invited*)", Y. Fujimoto, The 1st International Symposium on High Power Laser Science and Engineering (HPLSE2014), **C-5**, 16-19 March, 2014 in Suzhou city, Jiangsu province, China.
- 4) "Development on advanced functional optical fibers and materials in ILE - (*Planary talk*)", Y. Fujimoto, The 2nd International Workshop on Photoelectric Materials and Symposium on Functional Glasses, **PT-04**, 15-18 May, 2014 in Hangzhou, China
- 5) "Visible short pulse generation in waterproof fluoro-aluminate glass fibers using graphene thin film", T. Suzuki, R. A. M. Ochante, M. Murakami, T. Hirayama, M. Yoshida, O. Ishii, M. Yamazaki, H. Shiraga, and Y. Fujitomo, CLEO:2014, **SM10.6**, San Jose McEnery Convention Center, USA, 8-13 June 2014, Technical Digest Series. (*Selected audio slide-cast (recorded presentation) in Optics InfoBase permanently*)
- 6) "Visible fiber lasers excited by GaN laser diodes - (*invited*)", Y. Fujimoto, 3rd Laser Display Conference 2014, 19th-20th June, 2014, National Chung Hsing University, Taichung, Taiwan.
- 7) "New materials and new wavelength fiber lasers - (*invited*)", Y. Fujimoto, The 2015

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- EMN Optoelectronics Meeting, **D20**, 24th-27th April 2015, Beijing Xijiao Hotel, Beijing, China.
- 8) "Novel Design of Simple and Compact Tunable Fiber Laser", Y. Fujitomo, O. Ishii, and M. Yamazaki, CLEO:2015, **JTh2A.95**, San Jose McEnery Convention Center, USA, 8-13 June 2015, Technical Digest Series.
 - 9) "Simple and Compact Visible Tunable Fiber Laser", Y. Fujimoto, O. Ishii, and M. Yamazaki, CLEO®Europe-EQEC 2015, **CJ.P.9**, 21-25 June 2015, ICM - International Congress Centre, Munich, Germany.
 - 10) "Development of Multi-Color Visible Short Pulse Glass Fiber Laser", S. Kajikawa, Y. Fujimoto, M. Yoshida, O. Ishii, and M. Yamazaki, CLEO®Europe-EQEC 2015, **CJ.P.38**, 21-25 June 2015, ICM - International Congress Centre, Munich, Germany.
 - 11) "Development of Low Photo-Darkening Yb-Doped Silica Glass Fiber by Co-Doping of Group 2 Element", Y. Sakaguchi, Y. Fujimoto, M. Masuda, N. Miyanaga, and H. Nakano, CLEO®Europe-EQEC 2015, **CJ.P.47**, 21-25 June 2015, ICM - International Congress Centre, Munich, Germany.
 - 12) "Frontiers in new materials and new wavelength fiber lasers - **(invited)**", Y. Fujimoto, The 20th Opto Electronics and Communications Conference (OECC 2015), **JWeA.31**, 28th June – 2nd July 2015, Shanghai Everbright Convention Center, Shanghai, China.
 - 13) "Rare Earth Doped Fiber Lasers Based on Zeolite Method - **(invited)**", Y. Fujimoto, The 4th International Workshop on Specialty Optical Fibers (WSOF'2015), **WF1A.4**, 4th-6th November 2015, Hotel ICON, Kowloon, Hong Kong SAR, China.
 - 14) "Generation of red Q-switch pulse laser in Pr-doped double-clad structured waterproof fluoride glass fiber with graphene thin film", S. Kajikawa, T. Terao, S. Motokoshi, M. Yoshida, O. Ishii, M. Yamazaki, Y. Fujimoto, OPIC 2016, ALPS in OPTICS & PHOTONICS International Congress 2016, **ALPS6-5**, May 17, 2016, the Conference Center, Pacifico Yokohama (Yokohama, Japan).
 - 15) "Laser oscillation in low photo-darkening Yb-doped silica glass fiber by co-doping of group-2 element", Y. Sakaguchi, Y. Fujitomo, N. Miyanaga, H. Nakano, CLEO:2016, **SM3Q.2**, San Jose McEnery Convention Center, USA, 8-13 June 2016, Technical Digest Series.
 - 16) "Visible laser oscillation in single-mode Pr-doped double-clad structured waterproof fluoro-aluminate glass fiber", S. Kajikawa, T. Terao, S. Motokoshi, M. Yoshida, O. Ishii, M. Yamazaki and Y. Fujitomo, CLEO:2016, **SM3Q.4**, San Jose McEnery Convention Center, USA, 8-13 June 2016, Technical Digest Series.

Attachments: Publications a) and b)